Nuclear Physics B214 (1983) 189–200

A MEASUREMENT OF CHARGE PROPERTIES OF QUARK JETS AT PETRA

PLUTO COLLABORATION

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Received 29 November 1982

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The charge properties of quark jets produced in e^+e^- annihilation at 30 GeV c.m. energy have been investigated with the PLUTO detector. We find that the mean absolute value of the jet charge $\langle \ |Q_{\rm jet}| \ \rangle = 0.55 \pm 0.25$ is small compared to the expectation from statistical models. Long-range charge correlations are observed. These results indicate that the sign of the primary quark charge can be obtained with high probability from the charge of the jet and its distribution in the jet.

I. Introduction

According to the standard model of electroweak interactions of Glashow, Salam and Weinberg, the production of quarks in $e^+e^- \rightarrow q\bar{q}$ is uniquely related to their charges. Therefore experimental tests of this model are possible if the charges of these primary quarks can be estimated from the properties of the observed hadron jets. In particular, at the present PETRA energies of 36 GeV a charge asymmetry of 36% for $\frac{1}{3}$ charged quarks is expected.

Fragmentation models [1,2] predict that the particle charge distribution in momentum-space is strongly correlated with the charge and the momentum of the primary quark. However, the distribution is mainly dependent on the sign of the quark charge but only weakly on its absolute value. The study of the charge distribution is important not only for its relevance to electroweak effects but also for the understanding of the fragmentation process itself.

In this paper we study charge distributions in quark jets produced at PETRA in the energy range from 27 to 32 GeV. The main emphasis is put on quantities which are related to the charge of the primary quark.

We first investigate the charge of jets originating from the fragmentation of quarks. Since the difference between the quark charge and the jet charge is made up from particles 'leaking' out of the jet, the observation of a small mean absolute value of the jet charge would indicate that there is on average only little leakage. In this case the sign of the jet charge is strongly correlated to the sign of the primary jet charge.

We also study the charge distribution in rapidity-space. Because fragmentation is a soft process we expect that the primary quark is likely to be found in the fastest particles. This effect leads to long range charge correlations which are actually observed. From these results we estimate the reliability with which the charge of the primary quark can be determined from the charge properties of the jet.

Results on charge distribution in e^+e^- annihilation have already been published [3–5]. In particular, the TASSO experiment [5] has reported on the observation of long-range charge correlations.

2. Phenomenological fragmentation models

The formation of hadron jets in e^+e^- annihilation can be visualized in the simplified picture sketched in fig. 1. In the colour field of the two primary quarks, secondary quark-antiquark pairs are formed. Then quarks and antiquarks from the primary pair as well as those from the secondaries combine with quarks and antiquarks adjacent in rapidity-space. Thus mesons are generated. In this picture the primary quarks are always found in the leading mesons and the charge flow across any boundary in rapidity is 0 or 1.

In the popular Field-Feynman [1] model (FF) the strict order in rapidity is partially disturbed by a statistical procedure. Here the fraction of momentum taken

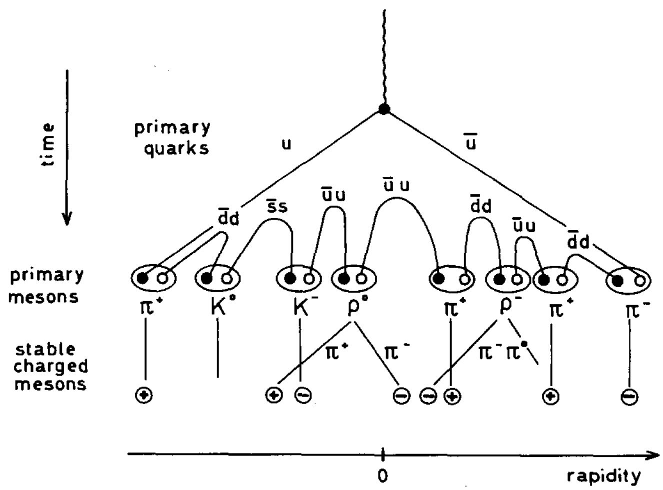

Fig. 1. Schematic graph of the development of quark jets in $e^+e^- \to q\bar{q}$.

by the first meson (containing the primary quark) of a jet is chosen according to a probability function (which determines the fragmentation function). The next meson's momentum is obtained analogously from the remaining momentum using the same function. This recursive procedure is repeated until the energy is exhausted. It leads to a much smaller degree of charge order than the naive scheme of fig. 1. In the FF model both the order in rapidity and the momentum distribution of mesons are completely determined by the fragmentation function. However, there is no compelling theoretical necessity for this close connection. As the momentum distributions of the FF model are well adjusted to experimental data we consider in the following only models that agree in this respect, but which may differ in the predicted charge distribution.

The experimental charge distributions are distorted considerably by measurement errors, acceptance losses and primary mesons decaying into secondary mesons. Corrections of charge distributions for these effects are difficult because the Monte Carlo programs in use do not contain adjustable charge correlation parameters. As a first step we therefore compare the observed uncorrected results to phenomenological models which are subjected to a simulation of the measurement process. The following simple models are considered:

(i) the model of Field and Feynman (FF);

(ii) same as (i) but the order in rapidity of the primary mesons is random (FFR);

(iii) same as (i) but the primary mesons have the strict order suggested by fig. 1 (FFO);

(iv) same as (i) but the order of the primary mesons is randomized within each jet (FFRJ);

(v) the charges of the observed particles in the data are randomized (RC).

We use a FF Monte Carlo program based on the prescription of ref. [1] but including c and b quark production* which reproduces the observed inclusive particle momentum distributions. Also the ratio of strongly decaying vector mesons to stable mesons (π, K) is consistent with experiment. Hard gluon bremsstrahlung is neglected. Its influence is small for 2-jet topologies as selected by the requirement on the thrust of $T > 0.8$ (see below).

The alternative models (ii) to (iv) are obtained from the FF model by retaining particle rapidities but modifying the particle assignments for the primary mesons. Thus the rapidity configuration of the events is essentially unchanged except for a slight readjustment of the particle momenta to conserve energy and momentum in the modified event.

Therefore all models give the same momentum distribution of the hadrons. The models (i), (iii) and (iv) should have the same distribution of the total charge of the jets. Model (v) does not correspond to a conceivable physical model but is interesting as an upper limit for a random charge distribution.

* The decay mechanism of mesons containing a heavy quark (c, b) has been adopted from ref. [2].

3. Data acquisition and selection criteria

The data used for this analysis were taken with the PLUTO detector [6] at the e^+e^- storage ring PETRA in the energy range 27 GeV $< E_{cm} <$ 32 GeV. Charged particles are measured in 13 cylindrical proportional chambers which cover 87% of 4π steradians and which operate in an axial magnetic field of 1.65 T. Photons are detected in lead scintillator sandwich calorimeters covering 97% of the full solid angle.

In this analysis all charged particles are assumed to be pions. In order to select hadronic events from background (mainly from beam-gas interaction, QED and $\gamma\gamma$ reactions) and to suppress incompletely measured events the following cuts were applied:

(a) the visible energy must exceed 40% of the c.m. energy E_{cm};

(b) at least 5 charged particles per event with at least 2 in each jet are required;

(c) to further reduce $\tau\bar{\tau}$ contamination, events with less than 7 charged particles must have at least one jet with an invariant mass greater than 1.5 GeV/c^2;

(d) the thrust has to be greater than 0.8 to ensure selection of 2-jet events;

(e) the angle θ between the thrust-axis and the beam direction has to fulfil the condition $|\cos\theta| < 0.75$.

The selected events were visually inspected to reduce the contamination of higher order QED processes and cosmic ray showers. After these cuts we obtained 750 events for further analysis (60% of the total data).

Although the data were taken in the energy range from 27 to 32 GeV with a mean value of 30.04 GeV, the Monte Carlo events were generated at a single energy of 30 GeV. Here the same cuts were applied as described above. The average charged multiplicity of the Monte Carlo events differed from that of the data by about 5%. We adjusted the multiplicity distribution in the Monte Carlo generation procedure to reproduce exactly the distribution of the data. This is necessary, because charge conservation induces a multiplicity dependent bias on all correlation measures.

The rapidity distributions of the data and the Monte Carlo agree well within the statistical errors. The observed averages are $\langle |y^{\text{data}}| \rangle = 1.61 \pm 0.02$ and $\langle |y^{\text{FF}}| \rangle = 1.61 \pm 0.01$. Also the distributions of the charges observed in each event agree. Here the averages are $\langle |Q_{\text{event}}^{\text{data}}| \rangle = 1.43 \pm 0.04$ and $\langle |Q_{\text{event}}^{\text{FF}}| \rangle = 1.38 \pm 0.03$. The agreement shows that acceptance and reconstruction losses are well reproduced in the Monte Carlo programs.

4. Results

4.1. JET CHARGE

We define the jet charge Q_{jet} as the sum of the charges of all *primary* particles of the jet with rapidity y greater than zero. The rapidity, $y = \frac{1}{2}\ln[(E+p_{\parallel})/(E-p_{\parallel})]$, is computed with respect to the thrust-axis of the event. The observed (or detector-simulated) jet charge $Q_{\rm jet}^{\rm observed}$ is usually different from $Q_{\rm jet}$, because secondaries of unstable particles cross the jet boundary $y = 0$ and because the events are distorted by the measurement process. Of the two jets the one with the lower multiplicity is affected least by particle losses. Therefore we use the charge of this jet in our analysis.

Fig. 2 shows the distribution of the observed absolute values of jet charges together with the expectations from the FF model and its randomized version (FFR). It is seen that the FFR model gives higher values of the jet charge than the data. Based on the mean values of the distributions (table 1) 1.243 ± 0.036 (FFR) and 1.045 ± 0.034 (data) we can exclude such a statistical model by 4 standard deviations. From the FF model we obtain 1.044 ± 0.023 in very good agreement with the data point. To assess the sensitivity of this agreement to the underlying true jet charge $\langle\ |Q_{\rm jet}|\ \rangle$ we use the following one-dimensional interpolation procedure which is justified by the good agreement of the differential charge distribution of the data and the FF model.

The FF Monte Carlo consists of two subsamples where the jet charge is zero or ± 1. Higher values of the jet charge do not occur because in the model only one quark is exchanged across the jet boundary $y = 0$. As a result of detector effects and the decay of primary mesons, the resulting jet charges (table 1) for these two

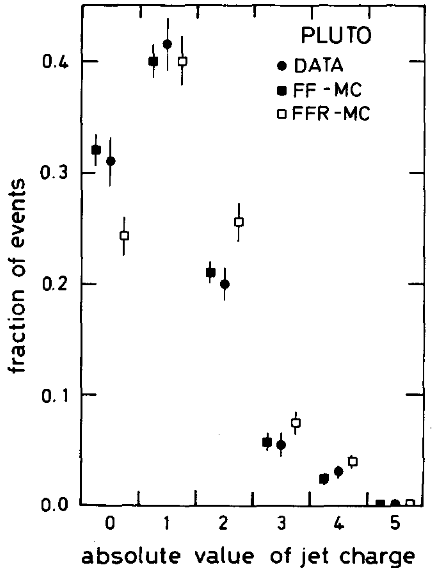

Fig. 2. Distribution of the absolute value of the jet charge. The data are compared to the FF model and to its randomized version (FFR).

TABLE 1

Mean value of the absolute jet charge. FF ($Q = \pm 1$) and FF ($Q = 0$) denote subsamples of the FF model, where the jet charge before the simulation of the measurement process is ± 1 and 0, respectively

Model	$\langle \lvert Q_{jet}^{observed} \rvert \rangle$
RC	1.313 ± 0.017
FFR	1.243 ± 0.036
FF	1.044 ± 0.023
FF ($Q_{jet} = \pm 1$)	1.138 ± 0.031
FF ($Q_{jet} = 0$)	0.932 ± 0.033
data	1.045 ± 0.034

subsamples are $\langle \lvert Q_{jet}^{observed} \rvert \rangle = 0.932 \pm 0.033$ ($Q_{jet} = 0$) and $\langle \lvert Q_{jet}^{observed} \rvert \rangle = 1.138 \pm 0.031$ ($Q_{jet} = \pm 1$), respectively. Assuming real jet charges of 0 and 1, a linear interpolation gives a corrected mean absolute value of the jet charge $\langle \lvert Q_{jet} \rvert \rangle = 0.55 \pm 0.25$ for our data, where the quoted error includes a statistical error of ± 0.20 and a systematic uncertainty of ± 0.15 (see below). If we also allow charged jets with $Q_{jet} = \pm 2$, our result for $\langle \lvert Q_{jet} \rvert \rangle$ would be slightly decreased. But in the worst and very unlikely case of no jets with charge ± 1 the decrease would amount to about half the quoted error. We have checked that this result does not depend on the selection of the low multiplicity jet for the computation of $\lvert Q_{jet} \rvert$ and that a fit of the two-dimensional distribution of $Q_{jet\,1}^{observed}$ versus $Q_{jet\,2}^{observed}$ gives almost identical results. The systematic uncertainty is due to the large difference between true and observed average jet charge. From Monte Carlo studies we find that this difference is caused mainly by uncorrelated particle losses or by the generation of additional particles through γ-ray conversion and to a smaller extent by false association of particles with jets. The uncorrelated contribution is reproduced very well in the Monte Carlo simulation as can be checked by comparing the observed event charges of the data and the Monte Carlo samples. From this comparison we compute a systematic uncertainty of the jet charge of ± 0.11. The size of the latter effect (which leaves the event charge unchanged) depends on the fragmentation model underlying the Monte Carlo simulation program. To estimate its contribution to the uncertainty we have compared the results with the Lund Monte Carlo [2] which includes gluons and has a different rapidity distribution near $y = 0$. We have also modified the amount of vector meson production in the FF model and have eliminated low rapidity particles with $\lvert y \rvert < 0.5$. The systematic uncertainty derived from these model changes is ± 0.10.

The small value obtained for $\langle \lvert Q_{jet} \rvert \rangle$ implies that there is only a small charge leakage out of the jet, consistent with the mechanism of the Field-Feynman fragmentation in which only a single quark crosses the jet boundary. The small leakage implies a strong correlation between the signs of the jet charge and of the primary quark charge. This correlation will be studied in subsect. 4.5. as a means for determining the sign of the primary quark charge.

In the following we consider only Field-Feynman type models that are compatible with the experimental value found for $\langle\ |Q_{\mathrm{jet}}|\ \rangle$, i.e. models FF, FFO and FFRJ. These models differ only in the degree of charge order within the jet.

4.2. TWO-PARTICLE CORRELATIONS

The preceding result has shown that the charges of the particles are not randomly distributed among the particles in an event. We next investigate the distribution of the charge within the jet. We first look at the charge correlation $C_{\mathrm{a}} = \langle -q_i \cdot q_j \rangle$ of particles *adjacent* in rapidity. C_{a} will be positive (negative) if opposite (like) sign particles dominate. Since the total charge of an event is zero (before measurement) a trivial non-zero correlation C_{a_0} is expected even from a purely statistical distribution. Using the RC model we obtain $C_{\mathrm{a}_0} = 0.079 \pm 0.005$.

The average of C_{a} found for our data is $+0.16 \pm 0.01$, much higher than the statistical expectation C_{a_0}. Such a local charge compensation can be due to a genuine charge order, to primary meson decay (e.g. from vector mesons) or to both. The small relative differences between the Monte Carlo models given in table 2 indicate that vector meson decay is the dominant source of local charge compensation. Although the FFR model has already been excluded by its jet charge, it is listed here to show the pure contribution from vector meson decay.

The good agreement of the data and the FF model and the small deviation from the FFRJ model should not be taken as a proof of charge order inside jets. Rather it demonstrates that the amount of vector meson production and the jet charge in these models are well adjusted.

A genuine charge order can be investigated by looking for long range correlations which are unbiased by hadron decay. For this purpose we measure the charge correlation $C_{\ell} = \langle -q_{\ell} \cdot q_{\ell'} \rangle$, where ℓ (ℓ') is the *leading* particle of jet 1 (2). From

TABLE 2

Two-particle charge correlations for particles adjacent in rapidity (C_{a}) and for the leading particles of the two jets (C_{ℓ})

	$C_{ij} = \langle -q_i \cdot q_j \rangle$	
Model	C_{a} (adjacent particles)	C_{ℓ} (leading particles)
FFRJ	0.147 ± 0.008	0.000 ± 0.024
FF	0.154 ± 0.008	0.006 ± 0.024
FFO	0.183 ± 0.008	0.057 ± 0.024
FFR	0.121 ± 0.012	
data	$0.160 \pm .011$	$0.085 \pm .036$

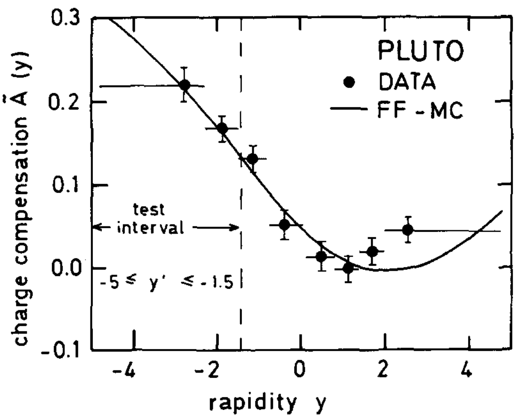

Fig. 3. Compensation of the charge of particles in the test interval $-5 < y' < -1.5$ as a function of rapidity. For the definition of $\tilde{A}(y)$ see subsect. 4.3.

our data we obtain $C_\ell = 0.085 \pm 0.036$ which is 2 S.D. larger than the statistical expectation (FFRJ) which is 0.000 ± 0.024*.

The results of C_ℓ for the relevant models are also listed in table 2. A comparison indicates that the observed correlation might be stronger than that for the FF model. The data agree best with the FFO model where the primary quark is always found in the fastest particle of the jet.

4.3. CHARGE COMPENSATION AS A FUNCTION OF RAPIDITY

We now investigate how the charges compensate each other in different regions of rapidity. Similar work has already been published by the TASSO collaboration [5]. We define an asymmetry $A(y, y') = 2P(y, y') - 1$ where $P(y, y')$ is the probability of finding opposite charges for two particles located at given rapidities y and y' (for zero charge compensation P is equal to 0.5 and A is zero). Fig. 3 shows

$$\tilde{A}(y) = \frac{\int_{-5}^{-1.5} A(y, y')\rho(y, y')\,\mathrm{d}y'}{\int_{-5}^{-1.5} \rho(y, y')\,\mathrm{d}y'},$$

which is obtained by weighting the asymmetry $A(y, y')$ with the two-particle density $\rho(y, y')$ and averaging over all test particles out of the high rapidity interval $-5 \leqslant y' \leqslant -1.5$. $\tilde{A}(y)$ is high near the test interval demonstrating the short range charge compensation which we have already observed in the two-particle correlations. It decreases to zero near $y = 0$ and rises again with increasing y to a value which is separated by about 3 standard deviations from zero. This result demon-

* Note that the trivial charge correlation from charge conservation is very small for the leading particles if the smallness of the jet charges is taken into account.

strates that there is also a long range correlation. The solid curve in fig. 3 shows that there is qualitative agreement with the FF model.

The analysis of $\tilde{A}(y)$ supports the conclusions already drawn from the two particle correlations, i.e. that there is a long range charge correlation which is explained by the hypothesis that the primary quarks are found predominantly in the leading particles of the jets.

4.4. DIPOLE CORRELATIONS

The next term in the multipole expansion of the charge distribution in rapidity space after the average value is the "dipole moment" D_{jet}. Here we define

$$D_{\text{jet}} = \sum_{i \in \text{jet}} q_j (y_i - y_m),$$

where

$$y_m = \frac{\sum_{i \in \text{jet}} |q_i| \, y_i}{\sum_{i \in \text{jet}} |q_i|},$$

is the rapidity of the centre of gravity of all charges in the jet. The variable D_{jet} is independent of Q_{jet}, in contrast to the "weighted jet charge" as proposed in ref. [1]. Therefore we have preferred to use the "dipole moment".

A correlation of the charge distributions of the two jets will produce a correlation $C_D = \langle D_{\text{jet 1}} \cdot D_{\text{jet 2}} \rangle$ different from zero. Table 3 summarizes the results for the data and the Monte Carlo models using three different event cuts for the rapidity of the fastest particle.

The data show a three standard deviation correlation with the main contribution apparently coming from events with high rapidity particles. These effects would suggest the existence of long range correlations. The agreement with FF is good, whereas in a random distribution (FFRJ) only a small correlation would be expected and this is due to particle decays which cross the jet boundary.

TABLE 3
Dipole correlations of the two jets

Model	$\langle D_{\text{jet 1}} \cdot D_{\text{jet 2}} \rangle$			
	all events	$\|y\|_{\max} < 2$	$2 < \|y\|_{\max} < 3$	$3 < \|y\|_{\max}$
FFRJ	0.03 ± 0.08	0.20 ± 0.15	0.02 ± 0.08	0.03 ± 0.15
FF	0.21 ± 0.07	0.02 ± 0.14	0.11 ± 0.08	0.35 ± 0.14
FFO	0.46 ± 0.07	0.11 ± 0.13	0.22 ± 0.07	0.82 ± 0.14
data	0.28 ± 0.09	-0.03 ± 0.10	0.17 ± 0.09	0.56 ± 0.23

Columns 3 to 5 are subsamples with restrictions on high-rapidity particles: no particle with $|y| > 2$ (column 3), no particle with $|y| > 3$ but at least one particle with $|y| > 2$ (column 4), at least one particle with $|y| > 3$ (column 5)

4.5. ASSIGNMENT OF THE PRIMARY QUARK CHARGE TO JETS

The observed charge correlations indicate that the charge of a jet and the charge distribution inside the jet are correlated with the charge of the primary quark that generated the jet. Therefore we use the FF type fragmentation models to calculate probabilities for correct identification of the primary quark charges.

We use the observed charge of jet 1 and the charges q_ℓ and $q_{\ell'}$ of the fastest charged particle in jet 1 and jet 2, respectively, to define 5 different event classes which are listed in table 4. For these five classes we estimate the probabilities that they are produced by a certain $q\bar{q}$ pair. To do so we use the FF model and the FFO model because the observed charge correlations lie between those expected in these two models. In this calculation we assume an ideal detector which detects all quasi-stable particles and has negligible measurement errors. The results are displayed in tables 4a and 4b.

As an example we discuss event class I which amounts to about 25% of all events. In this class $Q_{\text{jet 1}}$, q_ℓ are positive and $Q_{\text{jet 2}}$ and $q_{\ell'}$, are negative. Jet 1 is generated

TABLE 4
Distribution of primary quark charges for different jet classes

(a)

Class #	$Q_{\text{jet}}^{\text{observed}}$	q_ℓ	$q_{\ell'}$	Quark charge $+\frac{2}{3}$	$+\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{2}{3}$	Σ
I	+	+	−	15.1	4.4	0.9	1.8	22.2
II	+	±	±	17.9	5.5	1.9	4.4	29.7
III	0	+	−	10.4	3.5	2.2	4.2	20.3
IV	+	−	+	5.0	1.6	0.8	2.3	9.7
V	0	±	±	7.4	2.8	2.5	5.4	18.1
Σ	all classes			55.8	17.8	8.3	18.1	100.0

(b)

Class #	$Q_{\text{jet}}^{\text{observed}}$	q_ℓ	$q_{\ell'}$	Quark charge $+\frac{2}{3}$	$+\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{2}{3}$	Σ
I	+	+	−	20.4	5.2	0.4	0.6	26.6
II	+	±	±	15.3	4.7	1.8	2.4	24.2
III	0	+	−	13.1	5.3	1.1	2.5	22.0
IV	+	−	+	4.2	1.2	1.5	3.5	10.4
V	0	±	±	6.2	2.9	2.3	5.4	16.8
Σ	all classes			59.2	19.3	7.1	14.4	100.0

The classes are defined by the charge of the jet Q_{jet}, that of the leading particle q_ℓ and that of the leading particle in the opposite jet $q_{\ell'}$. The last column gives the relative frequency of the jet classes. The numbers are obtained from the FF model (a) and the FFO model (b) by quarks with charges $+\frac{2}{3}$, $+\frac{1}{3}$, $-\frac{1}{3}$, $-\frac{2}{3}$ with the relative frequencies of 15.1 (20.4), 4.4 (5.2), 0.9 (0.4), 1.8 (0.6) % where the first numbers correspond to the FF model and the number in brackets to the FFO model. The reliability for the assignment of a positive quark charge ($+\frac{2}{3}$ or $+\frac{1}{3}$) to the jet 1 is 76% (92%). Here the reliability is defined as the ratio of the difference between correct and wrong assignments to the sum. For classes I to III ($\approx 70\%$ of all events) this reliability drops to about 58% (76%). Similar results have been obtained in ref. [7].

Of course our estimates are slightly model dependent. A direct estimate can be obtained from the measurement of the leading particle correlation. If the probability that a quark produces a jet with a leading particle of the same sign of charge is w then the expected correlation is $C_{\ell} = (2w - 1)^2$. Thus we obtain from our measured value of C_{ℓ} a probability $w = 0.65 \pm 0.04$ corresponding to a reliability of 55% to identify the sign of the primary quarks' charge correctly for those events where q_{ℓ} and $q_{\ell'}$ are different.

5. Summary and conclusions

We observe small jet charges. This means that the net charge leakage across the jet boundaries is small and can be explained by models where only one quark-antiquark loop crosses the $y = 0$ boundary. The measurement of two-particle charge correlations, of the charge distribution in rapidity, and of dipole correlations suggests strongly that the primary quark-antiquark pair plays a special role in the development of the jet and is found predominantly in the fast particles. There are indications that the long range charge correlations are underestimated in the FF model. From our measurement of the average jet charge and of the correlation of the charges of the leading mesons we demonstrate that the signs of the charges of the primary quarks can be determined with good reliability.

We wish to thank the members of the DESY Directorate for the hospitality extended to the University groups. We thank Dr. J. Dainton for helpful discussions. We are indebted to the PETRA machine group and the DESY computer center for their excellent performance during the experiment. We gratefully acknowledge the efforts of all engineers and technicians of the collaborating institutions who have participated in the construction and the maintenance of the apparatus.

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